

CURABLE COMPOSITIONS AND RAPID PROTOTYPING PROCESS USING THE
SAME

5

FIELD OF THE INVENTION

The present invention relates to curable compositions capable of providing articles having the combination of a good elongation at break and good high temperature resistance. In addition, the present invention relates to applications for
10 such compositions, such as their use in rapid prototyping processes.

BACKGROUND

In the field of curable compositions, for instance in the field of rapid prototyping compositions, high temperature resistance, elongation to break, and cure
15 speed are relevant parameters. Unfortunately, a composition providing good high temperature resistance often exhibits a poor elongation to break. One of the objectives of the present invention is to provide compositions yielding both a good high temperature resistance and a good elongation to break. Another objective is to provide compositions that furthermore have a good cure speed.

20 Examples of prior curable compositions are set forth in, for instance, U.S. Patent 5,476,748; U.S. Patent 5,707,780; U.S. Patent 5,972,563; U.S. Patent 5,981,616; U.S. Patent 6,313,188; U.S. Patent 6,368,769; European Patent Application 0360869; and Japanese Patent Application 11199647.

25 SUMMARY

The present invention provides compositions having both a good high temperature resistance and a good elongation to break. Furthermore, the present invention provides compositions that additionally have a good cure speed. Also, the present invention provides applications for the compositions, such as their use in a
30 rapid prototyping process.

In one embodiment, the present invention provides a curable composition comprising:

- (i) one or more aromatic epoxies; and
- (ii) one or more aliphatic epoxies;

wherein said composition, after full cure, has a heat deflection temperature under a pressure of 1.82 MPa of at least 105°C and an elongation at break of at least 1.5%.

In another embodiment, the present invention provides a curable composition having an E10 cure speed of less than 80 mJ/cm² and, after full cure, a heat deflection temperature under a pressure of 1.82 MPa of at least 125°C and an elongation at break of at least 2.5%.

Additional objects, advantages and features of the present invention are set forth in this specification, and in part will become apparent to those skilled in the art on examination of the following, or may be learned by practice of the invention. The inventions disclosed in this application are not limited to any particular set of or combination of objects, advantages and features. It is contemplated that various combinations of the stated objects, advantages and features make up the inventions disclosed in this application.

DETAILED DESCRIPTION

(A) Cationically curable component

The present compositions comprise at least one cationically curable component, *e.g.* at least one cyclic ether component, cyclic lactone component, cyclic acetal component, cyclic thioether component, spiro orthoester component, epoxy-functional component, and/or oxetane-functional component. Preferably, the present compositions comprise at least one component selected from the group consisting of epoxy-functional components and oxetane-functional components. Preferably, the compositions comprise, relative to the total weight of the composition, at least 20 wt% of cationically curable components, for instance at least 40 wt%, at least 60 wt%, at least 70 wt%, or at least 80 wt%. Generally, the compositions comprise, relative to the total weight of the composition, less than 99 wt% of cationically curable components, for instance less than 95 wt%, less than 90 wt%, or less than 85 wt%.

(A1) Epoxy-functional components

The present compositions preferably comprise at least one epoxy-functional component, *e.g.* an aromatic epoxy-functional component ("aromatic epoxy") and/or an aliphatic epoxy-functional component ("aliphatic epoxy"). Epoxy-functional components are components comprising one or more epoxy groups, *i.e.* one or more three-member ring structures (oxiranes) according to formula (1):



(1).

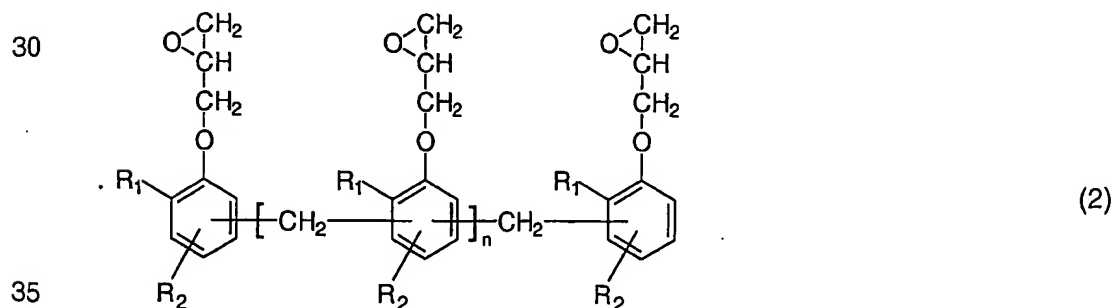
5 (A1-i) aromatic epoxies

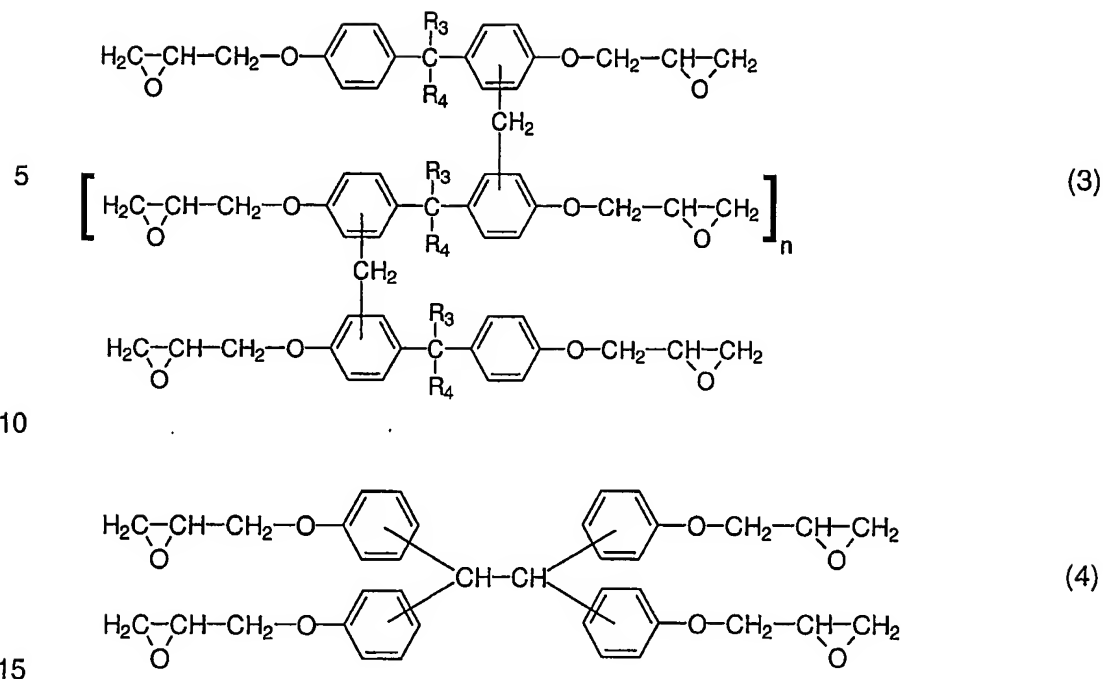
Aromatic epoxies are components that comprise one or more epoxy groups and one or more aromatic rings. The compositions may comprise one or more aromatic epoxies, *e.g.* two or more aromatic epoxies or three or more aromatic epoxies.

10 Examples of aromatic epoxies include aromatic epoxies derived from a polyphenol, *e.g.* from bisphenols such as bisphenol A (4,4'-isopropylidenediphenol), bisphenol F (bis[4-hydroxyphenyl]methane), bisphenol S (4,4'-sulfonyldiphenol), 4,4'-cyclohexylidenebisphenol, 4,4'-biphenol, or 4,4'-(9-fluorenylidene)diphenol. The bisphenols may be alkoxyated (*e.g.* ethoxylated and/or propoxylated) and/or
15 halogenated (*e.g.* brominated). Examples of bisphenol epoxies include bisphenol diglycidyl ethers.

Further examples of aromatic epoxies include triphenylolmethane triglycidyl ether, 1,1,1-tris(*p*-hydroxyphenyl)ethane triglycidyl ether, and aromatic epoxies derived from a monophenol, *e.g.* from resorcinol (for instance resorcin diglycidyl ether) or hydroquinone (for instance hydroquinone diglycidyl ether). Another
20 example is nonylphenyl glycidyl ether.

In addition, examples of aromatic epoxies include epoxy novolacs, for instance phenol epoxy novolacs and cresol epoxy novolacs. Commercial examples of cresol epoxy novolacs include, *e.g.*, EPICLON N-660, N-665, N-667, N-670, N-673, N-680, N-690, and N-695, manufactured by Dainippon Ink and Chemicals, Inc. Examples
25 of phenol epoxy novolacs include, *e.g.*, EPICLON N-740, N-770, N-775, and N-865, manufactured by Dainippon Ink and Chemicals Inc. Examples of epoxy novolacs also include those components represented by the following formulae (2), (3), or (4):





wherein

R₁ represents a hydrogen atom or a methyl group;

R₂ represents a hydrogen atom, an alkyl group having 1-4 carbon atoms (e.g. a methyl-, isopropyl-, or t-butyl group), a phenyl group, or an aralkyl group having 7-10 carbon atoms:

n represents an integer of 1-12 (e.g. 2-12 or 1-5);

R₃ represents a hydrogen atom or an alkyl group having 1-3 atoms (e.g. a methyl-, ethyl-, or n-propyl group); and

25 R₄ represents a hydrogen atom or an alkyl group having 1-3 atoms (e.g. a methyl-, ethyl-, or n-propyl group).

Examples of aromatic epoxies are also listed in U.S. Patent 6,410,127, which is hereby incorporated in its entirety by reference.

Preferably, the present compositions comprise, relative to the total weight of the composition, at least 10wt% of one or more aromatic epoxies, *e.g.* at least 25 wt%, at least 40wt%, at least 45 wt%, at least 50 wt%, or at least 55 wt%. Generally, the present compositions will comprise, relative to the weight of the composition less than 90 wt% of one or more aromatic epoxies, for instance less than 80 wt%.

(A1-ii) *aliphatic epoxies*

Aliphatic epoxies are components that comprise one or more epoxy groups and are absent an aromatic ring. The compositions may comprise one or more aliphatic epoxies.

5 Examples of aliphatic epoxies include glycidyl ethers of C₂-C₃₀ alkyls; 1,2 epoxies of C₃-C₃₀ alkyls; mono and multi glycidyl ethers of aliphatic alcohols and polyols such as 1,4-butanediol, neopentyl glycol, cyclohexane dimethanol, dibromo neopentyl glycol, trimethylol propane, polytetramethylene oxide, polyethylene oxide, polypropylene oxide, glycerol, and alkoxyated aliphatic alcohols and polyols.

10 In one embodiment, it is preferred that the aliphatic epoxies comprise one or more cycloaliphatic ring structures. For instance, the aliphatic epoxies may have one or more cyclohexene oxide structures, *e.g.* two cyclohexene oxide structures. Examples of aliphatic epoxies comprising a ring structure include hydrogenated bisphenol A diglycidyl ethers, hydrogenated bisphenol F diglycidyl ethers,
15 hydrogenated bisphenol S diglycidyl ethers, bis(4-hydroxycyclohexyl)methane diglycidyl ether, 2,2-bis(4-hydroxycyclohexyl)propane diglycidyl ether, 3,4-epoxycyclohexylmethyl-3,4-epoxycyclohexanecarboxylate, 3,4-epoxy-6-methylcyclohexylmethyl-3,4-epoxy-6-methylcyclohexanecarboxylate, di(3,4-epoxycyclohexylmethyl)hexanedioate, di(3,4-epoxy-6-
20 methylcyclohexylmethyl)hexanedioate, ethylenebis(3,4-epoxycyclohexanecarboxylate), ethanedioldi(3,4-epoxycyclohexylmethyl) ether, and 2-(3,4-epoxycyclohexyl-5,5-spiro-3,4-epoxy)cyclohexane-1,3-dioxane.

 Examples of aliphatic epoxies are also listed in U.S. Patent 6,410,127, which is hereby incorporated in its entirety by reference.

25 In one embodiment, the present compositions comprise, relative to the total weight of the composition, at least 5 wt% of one or more aliphatic epoxies, for instance at least 8 wt%, at least 10wt%, or at least 12 wt%. Generally, the present compositions will comprise, relative to the total weight of the composition, less than 50 wt% of aliphatic epoxies, for instance less than 40 wt%, less than 30 wt%, less than
30 25wt%, or less than 20 wt%.

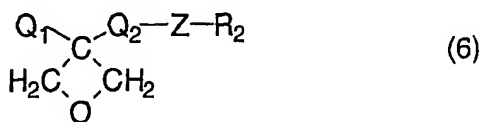
(A2) *Oxetane-functional components*

 The present compositions may comprise one or more oxetane-functional components ("oxetanes"). Oxetanes are components comprising one or
35 more oxetane groups, *i.e.* one or more four-member ring structures according to

formula (5):



5 Examples of oxetanes include components represented by the following formula (6):



10

wherein

Q₁ represents a hydrogen atom, an alkyl group having 1 to 6 carbon atoms (such as a methyl, ethyl, propyl, or butyl group), a fluoroalkyl group having 1 to 6 carbon atoms, an allyl group, an aryl group, a furyl group, or a thienyl group;

15 Q₂ represents an alkylene group having 1 to 6 carbon atoms (such as a methylene, ethylene, propylene, or butylene group), or an alkylene group containing an ether linkage, for example, an oxyalkylene group, such as an oxyethylene, oxypropylene, or oxybutylene group

Z represents an oxygen atom or a sulphur atom; and

20 R₂ represents a hydrogen atom, an alkyl group having 1-6 carbon atoms (e.g. a methyl group, ethyl group, propyl group, or butyl group), an alkenyl group having 2-6 carbon atoms (e.g. a 1-propenyl group, 2-propenyl group, 2-methyl-1-propenyl group, 2-methyl-2-propenyl group, 1-butenyl group, 2-butenyl group, or 3-butenyl group), an aryl group having 6-18 carbon atoms (e.g. a phenyl group, naphthyl group, anthranyl group, 25 or phenanthryl group), a substituted or unsubstituted aralkyl group having 7-18 carbon atoms (e.g. a benzyl group, fluorobenzyl group, methoxy benzyl group, phenethyl group, styryl group, cinnamyl group, ethoxybenzyl group), an aryloxyalkyl group (e.g. a phenoxymethyl group or phenoxyethyl group), an alkylcarbonyl group having 2-6 carbon atoms (e.g. an ethylcarbonyl group, propylcarbonyl group, or butylcarbonyl group), an alkoxy carbonyl group having 2-6 carbon atoms (e.g. an ethoxycarbonyl group, propoxycarbonyl group, or butoxycarbonyl group), an N-alkylcarbamoyl group having 2-6 carbon atoms (e.g. an ethylcarbamoyl group, propylcarbamoyl group, butylcarbamoyl group, or pentylcarbamoyl group), or a polyethergroup having 2-1000 carbon atoms.

35

Preferred oxetanes include those wherein

Q₁ represents a C₁-C₄ alkyl group (e.g. an ethyl group),

Z represents an oxygen atom,

Q₂ represents a methylene group, and/or

R₂ represents a hydrogen atom, a C₁-C₈ alkyl group, or a phenylgroup.

5 Some further examples of oxetanes include the following:

Oxetanes containing one oxetane ring in the molecule include, for instance, 3-ethyl-3-hydroxymethyloxetane, 3-(meth)allyloxymethyl-3-ethyloxetane, (3-ethyl-3-oxetanylmethoxy)methylbenzene, (3-ethyl-3-oxetanylmethoxy)benzene, 4-fluoro-[1-(3-ethyl-3-oxetanylmethoxy)methyl]benzene, 4-methoxy-[1-(3-ethyl-3-oxetanylmethoxy)methyl]benzene, [1-(3-ethyl-3-oxetanylmethoxy)ethyl] phenyl ether, isobutoxymethyl (3-ethyl-3-oxetanylmethyl) ether, isobornyloxyethyl (3-ethyl-3-oxetanylmethyl) ether, isobornyl (3-ethyl-3-oxetanylmethyl) ether, 2-ethylhexyl (3-ethyl-3-oxetanyl methyl) ether, ethyldiethylene glycol (3-ethyl-3-oxetanylmethyl) ether, dicyclopentadiene (3-ethyl-3-oxetanylmethyl) ether, dicyclopentenyl (3-ethyl-3-oxetanylmethyl) ether, 15 oxetanyl methyl) ether, dicyclopentenyl (3-ethyl-3-oxetanylmethyl) ether, tetrahydrofurfuryl (3-ethyl-3-oxetanylmethyl) ether, tetrabromophenyl (3-ethyl-3-oxetanylmethyl) ether, 2-tetrabromophenoxyethyl (3-ethyl-3-oxetanylmethyl) ether, tribromophenyl (3-ethyl-3-oxetanylmethyl) ether, 2-tribromophenoxyethyl (3-ethyl-3-oxetanylmethyl) ether, 2-hydroxyethyl (3-ethyl-3-oxetanyl methyl) ether, 2-20 hydroxypropyl (3-ethyl-3-oxetanylmethyl) ether, butoxyethyl (3-ethyl-3-oxetanylmethyl) ether, pentachlorophenyl (3-ethyl-3-oxetanylmethyl) ether, pentabromophenyl (3-ethyl-3-oxetanylmethyl) ether, bornyl (3-ethyl-3-oxetanylmethyl) ether, 2-phenyl-3, 3-dimethyl-oxetane, and 2-(4-methoxyphenyl)-3, 3-dimethyl-oxetane.

Oxetanes containing two or more oxetane rings in the molecule include, for instance, 3,7-bis(3-oxetanyl)-5-oxa-nonane, 3,3'-(1,3-(2-methylenyl)propanediylbis(oxymethylene))bis-(3-ethyloxetane), 1,4-bis[(3-ethyl-3-oxetanylmethoxy)methyl]benzene, 1,2-bis[(3-ethyl-3-oxetanylmethoxy)methyl]ethane, 1,3-bis[(3-ethyl-3-oxetanylmethoxy)methyl]propane, ethylene glycol bis(3-ethyl-3-oxetanylmethyl) ether, dicyclopentenyl bis(3-ethyl-3-oxetanylmethyl) ether, triethylene glycol bis(3-ethyl-3-oxetanylmethyl) ether, tetraethylene glycol bis(3-ethyl-3-oxetanylmethyl) ether, tricyclodecanediyl dimethylene (3-ethyl-3-oxetanylmethyl) ether, trimethylolpropane tris(3-ethyl-3-oxetanylmethyl) ether, 1,4-bis(3-ethyl-3-oxetanylmethoxy)butane, 1,6-bis(3-ethyl-3-oxetanylmethoxy)hexane, pentaerythritol tris(3-ethyl-3-oxetanylmethyl) ether, pentaerythritol tetrakis(3-ethyl-3-oxetanylmethyl) ether, polyethylene glycol bis(3-ethyl-3-oxetanylmethyl) ether, dipentaerythritol 35 ether, polyethylene glycol bis(3-ethyl-3-oxetanylmethyl) ether, dipentaerythritol

hexakis(3-ethyl-3-oxetanylmethyl) ether, dipentaerythritol pentakis(3-ethyl-3-oxetanylmethyl) ether, dipentaerythritol tetrakis(3-ethyl-3-oxetanylmethyl) ether, caprolactone-modified dipentaerythritol hexakis(3-ethyl-3-oxetanylmethyl) ether, caprolactone-modified dipentaerythritol pentakis(3-ethyl-3-oxetanylmethyl) ether, 5 ditrimethylolpropane tetrakis(3-ethyl-3-oxetanylmethyl) ether, ethoxylated bisphenol A bis(3-ethyl-3-oxetanylmethyl) ether, propoxylated bisphenol A bis(3-ethyl-3-oxetanylmethyl) ether, ethoxylated hydrogenated bisphenol A bis(3-ethyl-3-oxetanylmethyl) ether, propoxylated hydrogenated bisphenol A bis(3-ethyl-3-oxetanylmethyl) ether, ethoxylated bisphenol F (3-ethyl-3-oxetanylmethyl) ether.

10 In one embodiment, the present compositions comprise, relative to the total weight of the composition, at least 5 wt% of one or more oxetanes, *e.g.* at least 8 wt%, at least 10 wt%, at least 12 wt%, or at least 14 wt%. Generally, the present compositions comprise less than 50 wt% of oxetanes, *e.g.* less than 40 wt%, less than 35 wt%, less than 30 wt%, or less than 25 wt%.

15

(B) Free radical polymerizable components

In addition to one or more cationically curable components, the present invention may comprise one or more free radical curable components, *e.g.* one or more free radical polymerizable components having one or more ethylenically 20 unsaturated groups, such as (meth)acrylate (*i.e.* acrylate and/or methacrylate) functional components.

Examples of monofunctional ethylenically unsaturated components include acrylamide, N,N-dimethylacrylamide, (meth)acryloylmorpholine, 7-amino-3,7-dimethyloctyl (meth)acrylate, isobutoxymethyl(meth)acrylamide, isobornyloxyethyl 25 (meth)acrylate, isobornyl (meth)acrylate, 2-ethylhexyl (meth)acrylate, ethyldiethylene glycol (meth)acrylate, t-octyl (meth)acrylamide, diacetone (meth)acrylamide, dimethylaminoethyl (meth)acrylate, diethylaminoethyl (meth)acrylate, lauryl (meth)acrylate, dicyclopentadiene (meth)acrylate, dicyclopentenylloxyethyl (meth)acrylate, dicyclopentenyl (meth)acrylate, N,N- 30 dimethyl(meth)acrylamidetetrachlorophenyl (meth)acrylate, 2-tetrachlorophenoxyethyl (meth)acrylate, tetrahydrofurfuryl (meth)acrylate, tetrabromophenyl (meth)acrylate, 2-tetrabromophenoxyethyl (meth)acrylate, 2-trichlorophenoxyethyl (meth)acrylate, tribromophenyl (meth)acrylate, 2-tribromophenoxyethyl (meth)acrylate, 2-hydroxyethyl (meth)acrylate, 2-hydroxypropyl (meth)acrylate, vinylcaprolactam, N-vinylpyrrolidone, 35 phenoxyethyl (meth)acrylate, butoxyethyl (meth)acrylate, pentachlorophenyl

(meth)acrylate, pentabromophenyl (meth)acrylate, polyethylene glycol mono(meth)acrylate, polypropylene glycol mono(meth)acrylate, bornyl (meth)acrylate, and, methyltriethylene diglycol (meth)acrylate.

Examples of the polyfunctional ethylenically unsaturated components
 5 include ethylene glycol di(meth)acrylate, dicyclopentenyl di(meth)acrylate, triethylene glycol diacrylate, tetraethylene glycol di(meth)acrylate, tricyclodecanedioldimethylene di(meth)acrylate, trimethylolpropane tri(meth)acrylate, ethoxylated trimethylolpropane tri(meth)acrylate, propoxylated trimethylolpropane tri(meth)acrylate, tripropylene glycol di(meth)acrylate, neopentyl glycol di(meth)acrylate, both-terminal (meth)acrylic acid
 10 adduct of bisphenol A diglycidyl ether, 1,4-butanediol di(meth)acrylate, 1,6-hexanediol di(meth)acrylate, polyethylene glycol di(meth)acrylate, (meth)acrylate-functional pentaerythritol derivatives (e.g. pentaerythritol tri(meth)acrylate, pentaerythritol tetra(meth)acrylate, dipentaerythritol hexa(meth)acrylate, dipentaerythritol penta(meth)acrylate, or dipentaerythritol tetra(meth)acrylate), ditrimethylolpropane
 15 tetra(meth)acrylate, ethoxylated bisphenol A di(meth)acrylate, propoxylated bisphenol A di(meth)acrylate, ethoxylated hydrogenated bisphenol A di(meth)acrylate, propoxylated -modified hydrogenated bisphenol A di(meth)acrylate, and ethoxylated bisphenol F di(meth)acrylate.

In one embodiment, the present compositions comprise one or more
 20 components having at least 3 (meth)acrylate groups, for instance 3-6 (meth)acrylate groups or 5-6 (meth)acrylate groups.

If present, the compositions may comprise, relative to the total weight of the composition, at least 3 wt% of one or more free radical polymerizable components, for instance at least 5 wt% or at least 9 wt%. Generally, the compositions
 25 comprise, relative to the total weight of the composition, less than 50 wt% of free radical polymerizable components, for instance less than 35 wt%, less than 25 wt%, less than 20 wt%, or less than 15 wt%.

(C) Hydroxy-functional components

30 Preliminarily, hydroxy-functional components in this section (C) are understood to be absent curable groups (such as, e.g., acrylate-, epoxy-, or oxetane groups) and to be not selected from the group consisting of photoinitiators.

The present compositions may comprise one or more hydroxy-functional components. Hydroxy-functional components may be helpful in further
 35 tailoring mechanical properties of the present compositions upon cure. Hydroxy-

functional components include monols (hydroxy-functional components comprising one hydroxy group) and polyols (hydroxy-functional components comprising more than one hydroxy group).

Representative examples of hydroxy-functional components include

5 alkanols, monoalkyl ethers of polyoxyalkyleneglycols, monoalkyl ethers of alkyleneglycols, alkylene and arylalkylene glycols, such as 1,2,4-butanetriol, 1,2,6-hexanetriol, 1,2,3-heptanetriol, 2,6-dimethyl-1,2,6-hexanetriol, (2R,3R)-(-)-2-benzyloxy-1,3,4-butanetriol, 1,2,3-hexanetriol, 1,2,3-butanetriol, 3-methyl-1,3,5-pentanetriol, 1,2,3-cyclohexanetriol, 1,3,5-cyclohexanetriol, 3,7,11,15-tetramethyl-1,2,3-hexadecanetriol,

10 2-hydroxymethyltetrahydropyran-3,4,5-triol, 2,2,4,4-tetramethyl-1,3-cyclobutanediol, 1,3-cyclopentanediol, trans-1,2-cyclooctanediol, 1,16-hexadecanediol, 3,6-dithia-1,8-octanediol, 2-butyne-1,4-diol, 1,3-propanediol, 1,4-butanediol, 1,5-pentanediol, 1,6-hexanediol, 1,7-heptanediol, 1,8-octanediol, 1,9-nonanediol, 1-phenyl-1,2-ethanediol, 1,2-cyclohexanediol, 1,5-decalindiol, 2,5-dimethyl-3-hexyne-2,5-diol, 2,7-dimethyl-3,5-

15 octadiyne-2-7-diol, 2,3-butanediol, 1,4-cyclohexanedimethanol, polyoxyethylene and polyoxypropylene glycols and triols of molecular weights from about 200 to about 10,000, polytetramethylene glycols of varying molecular weight, poly(oxyethylene-oxybutylene) random or block copolymers, copolymers containing pendant hydroxy groups formed by hydrolysis or partial hydrolysis of vinyl acetate copolymers,

20 polyvinylacetal resins containing pendant hydroxyl groups; hydroxy-functional (e.g. hydroxy-terminated) polyesters and hydroxy-functional (e.g. hydroxy-terminated) polylactones, aliphatic polycarbonate polyols (e.g. an aliphatic polycarbonate diol), hydroxy-functional (e.g. hydroxy-terminated) polyethers (e.g. polytetrahydrofuran polyols having a number average molecular weight in the range of 150-4000 g/mol,

25 150-1500g/mol, or 150-750 g/mol), and combinations thereof.

In one embodiment, the compositions are absent substantial amounts of hydroxy-functional components. The absence of substantial amounts of hydroxy-functional components may decrease the hygroscopicity of the compositions and/or articles obtained therewith. For instance, the compositions may comprise, relative to

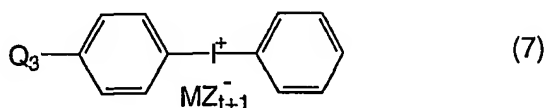
30 the total weight of the composition, less than 15 wt%, less than 10 wt%, less than 6 wt%, less than 4 wt%, less than 2 wt%, or about 0 wt% of hydroxy-functional components.

(D) Cationic photoinitiators

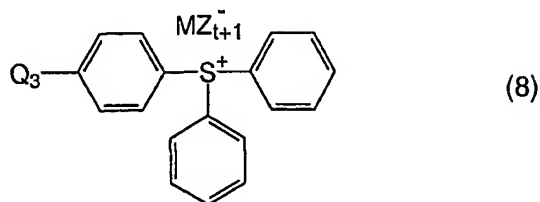
The present compositions preferably comprise one or more cationic photoinitiators, *i.e.* photoinitiators that, upon exposure to actinic radiation, form cations that can initiate the reactions of cationically polymerizable components, such as epoxies or oxetanes.

5 Examples of cationic photoinitiators include, for instance, onium salts with anions of weak nucleophilicity. Examples include halonium salts, iodosyl salts or sulfonium salts, such as are described in published European patent application EP 153904 and WO 98/28663, sulfoxonium salts, such as described, for example, in published European patent applications EP 35969, 44274, 54509, and 164314, or
10 diazonium salts, such as described, for example, in U.S. Patents 3,708,296 and 5,002,856. All eight of these disclosures are hereby incorporated in their entirety by reference. Other examples of cationic photoinitiators include metallocene salts, such as described, for instance, in published European applications EP 94914 and 94915, which applications are both hereby incorporated in their entirety by reference.

15 In one embodiment, the present compositions comprise one or more photoinitiators represented by the following formula (7) or (8):



20



25 wherein

Q_3 represents a hydrogen atom, an alkyl group having 1 to 18 carbon atoms, or an alkoxy group having 1 to 18 carbon atoms;

M represents a metal atom, *e.g.* antimony;

Z represents a halogen atom, *e.g.* fluorine; and

30 t is the valent number of the metal, *e.g.* 5 in the case of antimony.

In one embodiment, the present compositions comprise, relative to the total weight of the composition, 0.1-15 wt% of one or more cationic photoinitiators, for instance 1-10 wt%.

(E) Free radical photoinitiators

The compositions may employ one or more free radical photoinitiators. Examples of free radical photoinitiators include benzophenones (*e.g.* benzophenone, alkyl-substituted benzophenone, or alkoxy-substituted benzophenone); benzoin, *e.g.* benzoin, benzoin ethers, such as benzoin methyl ether, benzoin ethyl ether, and benzoin isopropyl ether, benzoin phenyl ether, and benzoin acetate; acetophenones, such as acetophenone, 2,2-dimethoxyacetophenone, 4-(phenylthio)acetophenone, and 1,1-dichloroacetophenone; benzil, benzil ketals, such as benzil dimethyl ketal, and benzil diethyl ketal; anthraquinones, such as 2-methylantraquinone, 2-ethylantraquinone, 2-tertbutylantraquinone, 1-chloroanthraquinone, and 2-amylantraquinone; triphenylphosphine; benzoylphosphine oxides, such as, for example, 2,4,6-trimethylbenzoyldiphenylphosphine oxide; thioxanthenes and xanthenes, acridine derivatives, phenazene derivatives, quinoxaline derivatives or l-phenyl-1,2-propanedione-2-O-benzoyloxime, l-aminophenyl ketones or l-hydroxyphenyl ketones, such as l-hydroxycyclohexyl phenyl ketone, phenyl (1-hydroxyisopropyl)ketone and 4-isopropylphenyl(1-hydroxyisopropyl)ketone, or triazine compounds, for example, 4"-methyl thiophenyl-1-di(trichloromethyl)-3,5-S-triazine, S-triazine-2-(stilbene)-4,6-bistrichloromethyl, and paramethoxy styryl triazine.

Further suitable free radical photoinitiators include the ionic dye-counter ion compounds, which are capable of absorbing actinic rays and producing free radicals, which can initiate the polymerization of the acrylates. *See*, for example, published European Patent Application 223587, and U.S. Patents 4,751,102, 4,772,530 and 4,772,541, all four of which are hereby incorporated in their entirety by reference.

In one embodiment, the present compositions comprise, relative to the total weight of the composition, 0.1-15 wt% of one or more free radical photoinitiators, for instance 1-10 wt%.

(F) Additives

Additives may also be present in the composition of the invention. Stabilizers are sometimes added to the compositions in order to prevent a viscosity build-up, for instance a viscosity build-up during usage in a solid imaging process. Preferred stabilizers include those described in U.S. Patent 5,665,792, the entire disclosure of which is hereby incorporated by reference. Such stabilizers are usually hydrocarbon carboxylic acid salts of group IA and IIA metals. Most preferred examples

of these salts are sodium bicarbonate, potassium bicarbonate, and rubidium carbonate. Alternative stabilizers are polyvinylpyrrolidones and polyacrylonitriles. Other possible additives are dyes, including dyes that change color upon cure. Examples of color-changing dyes include COPIKEM 20 (3,3-bis (1-butyl -2-methyl-H-indol-3-yl) - 1-(3H)-isobenzofuranone), COPIKEM 5 (2'-di (phenylmethyl) amino-6'-(diethylamino)spiro(isobenzofuran-1(3H),9'-(9H)xanthen)-3-one), COPIKEM 14 (a substituted phthalide), COPIKEM 7 (3-((4-dimethylamino)-phenyl)-3-(1-butyl-2-methylindol-3-yl) -6-dimethylamino) -1(3H)-isobenzofuranone), and COPIKEM 37 (2-(2-octoxyphenyl)-4-(4-dimethylaminophenyl)-6-(phenyl)pyridine). If present, the amount of color-changing dyes in the compositions is, relative to the total weight of the composition, preferably at least 0.0001 wt%, for instance at least 0.0005 wt%. In one embodiment, the amount of dye is, relative to the total weight of the composition, less than 1 wt%, *e.g.* less than 0.1 wt%. Even further examples of additives include antioxidants, wetting agents, antifoaming agents, thickening agents, photosensitizers (*e.g.* *n*-ethyl carbazole, benzoperylene, 1,8-diphenyl-1,3,5,7-octatetraene, or 1,6-diphenyl-1,3,5-hexatriene), and metallic-, organic-, inorganic-, or organic-inorganic hybrid fillers (*e.g.* silica particles, glass beads, or talc). The size of the fillers may vary and can be, for instance, in the nanometer range or in the micrometer range. In one embodiment, the present compositions comprise, relative to the total weight of the composition, less than 20 wt% of fillers, *e.g.* less than 10 wt%, less than 5 wt%, or about 0 wt%. In another embodiment, the present compositions comprise, relative to the total weight of the composition, up to 90 wt% of filler, *e.g.* 20-90 wt%, 40-90 wt%, or 60-90 wt%.

25 *Physical parameters*

The present compositions, after full cure, preferably have a heat deflection temperature ("HDT") under a pressure of 1.82 MPa (264 psi) of at least 105°C, for instance at least 110°C, at least 115°C, at least 120°C, or at least 125°C. The HDT (1.82 MPa) is generally below 300°C.

30 The present compositions, after full cure, preferably have an elongation at break of at least 1.5%, for instance at least 2.0%, at least 2.5%, at least 3%, or at least 3.5%. The elongation at break is generally below 50%.

The present compositions preferably have an E10 cure speed of less than 85 mJ/cm², for instance less than 80 mJ/cm², less than 70 mJ/cm², less than 60 mJ/cm², less than 55 mJ/cm², less than 50 mJ/cm², or less than 45 mJ/cm².

The physical condition of the present compositions may vary and can be, for instance, a liquid, a gel, a paste, or a solid. If the composition is a liquid, it preferably has a viscosity, at 30°C, of less than 1000 mPas, for instance less than 750 mPas, less than 650 mPas, less than 550 mPas, less than 450 mPas, or less than 350 mPas.

The present compositions, after full cure, preferably have a tensile strength of at least 35 MPa, for instance at least 40 MPa, at least 50 MPa, at least 60 MPa, or at least 70 MPa.

The present compositions, after full cure, preferably have a Young's modulus of at least 1500 MPa, for instance at least 2000 MPa, at least 2500 MPa, at least 2750 MPa, or at least 3000 MPa.

The present compositions, after full cure, preferably have a glass transition temperature (T_g) of at least 105°C, for instance at least 110°C, at least 120°C, at least 130°C, at least 140°C, or at least 150°C. The T_g is generally below 300°C.

Applications

The present compositions may be used, for instance, as coating compositions or as compositions for preparing a three dimensional object by rapid prototyping. The compositions may be cured by heat or any suitable form of radiation, *e.g.* electron beam radiation or actinic radiation, or mixtures thereof. For instance, the composition may first be cured to a certain extent by radiation and subsequently be post-cured by heat.

Rapid prototyping, sometimes also referred to as "solid imaging" or "stereolithography", concerns the imagewise curing of successive thin layers of a curable composition to form a three-dimensional object. *See, e.g.*, U.S. Patents 4,987,044; 5,014,207; 5,474,719; 5,476,748; and 5,707,780; which are all five hereby incorporated in their entirety by reference. A rapid prototyping process may for instance be described as:

- (1) coating a layer of a composition onto a surface;
- (2) exposing said layer imagewise to actinic radiation to form an imaged cross-section;
- (3) coating a further layer of the composition onto said imaged cross-section;
- (4) exposing said further layer imagewise to actinic radiation to form an additional imaged cross-section;

- (5) repeating steps (3) and (4) a sufficient number of times in order to build up a three-dimensional article;
- (6) optionally, post-curing the three-dimensional article.

5 The following examples are given as particular embodiments of the invention and to demonstrate the practice and advantages thereof. It is to be understood that the examples are given by way of illustration and are not intended to limit the specification or the claims that follow in any manner.

10 EXAMPLES

Table 1: Glossary

Commercial Name (Supplier)	Description
EPON 825 (Resolution Performance Products)	bisphenol A diglycidyl ether (aromatic epoxy)
EPICLON N-740 (Dainippon Ink & Chemical)	phenol epoxy novolac (aromatic epoxy)
HELOXY 64 (Resolution Performance Products)	nonylphenyl glycidyl ether (aromatic epoxy)
UVACURE 1500 (UCB Radcure)	3,4-epoxy cyclohexyl methyl-3,4-epoxy cyclohexyl carboxylate (aliphatic epoxy)
UVR 6000 (Dow Chemical)	3-ethyl-3-hydroxymethyl-oxetane (oxetane)
SR-399 (Sartomer)	monohydroxy dipentaerythritol pentaacrylate
IRGACURE 184 (Ciba Geigy)	1-hydroxycyclohexyl phenyl ketone
DAROCURE 1173 (Ciba Geigy)	2-hydroxy-2-methyl-1-phenyl-1-propanone
CPI-6976 (Aceto)	mixture of triarylsulfonium hexafluoroantimonate salts
SILWET L-7600 (OSI Specialities)	surfactant
BYK-A-501 (BYK-Chemie)	defoamer
PVP (Aldrich)	stabilizer (polyvinylpyrrolidone, Mw ca. 10,000)

15 Compositions were prepared by mixing the components listed in Table 2 (Examples 1-8) and Table 3 (Comparative Examples A-B), with amounts of the components being listed in parts by weight. The thus prepared compositions were subsequently analyzed in accordance with the Test Methods described below. The test results are also listed in Tables 2 and 3.

Table 2: Examples 1-8

Ingredients	Ex. 1	Ex. 2	Ex. 3	Ex. 4	Ex. 5	Ex. 6	Ex. 7	Ex. 8
EPON 825	42	39	50	42.1	40.5	34.0	42.4	38.4
EPICLON N-740	8	16		13	12.5	13.4	12.3	17.5
HELOXY 64					3.8			
UVACURE 1500	12.5	12.5	12.5	12.5	12.0	20.2	12.5	13
UVR 6000	20	15	20	15.5	15.5	15.5	16	16.6
SR399	12	12	12	11	10.6	11.0	11	9.2
CPI 6976	4	4	4	2.8	2.7	4	4	4
IRGACURE 184	1.5	1.5	1.5	2.8	2.7	1.6		1.6
DAROCURE 1173							1.6	
SILWET L-7600	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
BYK A501	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
PVP	0.005	0.005	0.005	0.005	0.005		0.005	0.005
Test results								
E_c [mJ/cm ²]	10.3	8.4	6.8	8.7	9.9	5.2	9.6	7.8
D_p [μm]	130	117	137	140	152	112	130	122
E_{10} [mJ/cm ²]	73.4	73.6	44.3	53.5	51.8	49.9	68.9	61.8
T_g [°C]	129.8	151	118	132	127	135	131	127
HDT (1.82 MPa) [°C]	110.7	129.3	109	125.5	119.6			
Young's modulus [MPa]	3013	3131	3000	2951	3048	3083	3138	3000
Elongation at break [%]	3.7	2.6	3.5	3.3	3.7	2.3	2.0	1.7
Tensile Strength [MPa]	71.4	60.8	71.4	68.7	75.2	55.7	49.7	46.0
Viscosity, 30°C [mPas]	334	675	275	575	520	420	490	

Table 3: Comparative Examples A and B

Ingredients	Comp. Ex. A	Comp. Ex. B
EPON 825	49.6	52.8
EPICLON N-740	16	16
UVR 6000	16	16.6
SR399	12	10.5
CPI 6976	3.6	4
IRGACURE 184	2.6	1.8
DAROCURE 1173	0.2	0.2
SILWET L-7600	0.02	0.02
BYK A501	0.005	0.005
Test results		
Ec [mJ/cm ²]	14.4	20.8
Dp [μm]	140	140
E10 [mJ/cm ²]	88.2	126.9
T _g [°C]	123	91
Young's modulus [MPa]	2979	3028
Elongation at break [%]	2.5	3.5
Tensile Strength after [MPa]	59.6	71.6
Viscosity, 30°C [mPas]	850	

TEST METHODS

(a) Tensile Strength, Young's modulus, and Elongation at Break

Tensile data was obtained by testing tensile bars ("dogbones") made by first consecutively imaging 150µm thick layers of the composition to be tested in a rapid prototyping machine. Each cross-sectional layer of the tensile bar was given exposure sufficient to polymerize the composition at a 250 µm depth, providing approximately 100 µm of overcure or engagement cure to assure adhesion to the previously coated and exposed layer. The layers were exposed with a laser emitting in the ultraviolet (UV) region at 354.7 nm. The resulting tensile bars/dogbones were approximately 150 mm long and had a cross-section in the narrowed portion of approximately 1cm x 1cm. After preparation of the tensile bar in the rapid prototyping machine, the tensile bar was removed from the machine, washed with tri(propyleneglycol) methyl ether ("TPM") and isopropanol, and placed in a post-curing apparatus ("PCA" sold by 3-D Systems, 10 bulb unit using Phillips TLK/05 40W bulbs). In the PCA, the tensile bar was post-cured first by subjecting it to 60 minutes of UV radiation at room temperature. After these 60 minutes, the UV radiation was stopped and the tensile bar was subjected to 160°C for two hours. The procedure of rapid prototyping a composition and post-curing a composition in the manner just described is understood herein to result in fully cured samples. The tensile tests to determine tensile strength, Young's modulus, and elongation at break were run one day after preparation of the tensile bar and in accordance with ASTM D638, which is hereby incorporated in its entirety by reference, except that no provision was made for controlling the room temperature and humidity and the bars were not equilibrated for 2 days. The reported data is the average of three measurements.

(b) Viscosity

The composition was added to a 250-mL screw cap bottle and heated to 30°C by placing it in a 30°C bath for at least one hour. The viscosity of the composition was then determined with a Brookfield DV-II+ Viscometer employing a #3 spindle.

(c) Glass Transition Temperature (T_g)

A fully cured specimen was prepared in the same manner as described above for the preparation of a tensile bar. Part of the specimen was placed

in a TA Instruments TMA 2940 at room temperature. The specimen was then heated with a ramp of 3°C/min from room temperature to 250°C under a nitrogen purge of 60 mL/min. A graph of dimension change over temperature was generated and analyzed by using TA Instrument Universal Analysis V2.6D software, which calculated the glass transition temperature from a sudden change in the slope of the thermal expansion curve.

(d) Heat Deflection Temperature (HDT)

Fully cured specimens for determining the HDT were prepared in the same manner as the above tensile bars, except that the dimensions of the specimens for the HDT measurements were 5 inch (12.7 cm) in length and 0.5x0.5 inch (12.7mm x 12.7mm) in cross-section. The HDT (under a pressure of 1.82 MPa) of the specimens was then determined according to ASTM D648-00a Method B, which is hereby incorporated in its entirety by reference, employing an ATLAS HDV2 Automated instrument.

(e) E10, D_p, and E_c

The photoproperties E_c (mJ/cm²), D_p (μm), and E10 (mJ/cm²) represent the photoresponse (in this case thickness of layer formed) of a particular formulation to exposure by a single wavelength or range of wavelengths. In the instant Examples and Comparative Examples, at least 20 grams of composition was poured into a 100 mm diameter petri-dish and allowed to equilibrate to approximately 30°C and 30% RH. The samples were then scanned in a line-by-line fashion using a focused laser beam of approximately 100-140 mW. The laser, a frequency tripled YAG laser, had an output wavelength of 354.7 nm and was pulsed at 80 KHz. The exposures were made in a square pattern approximately 20 mm by 20 mm. Six individual exposures were made at near constant laser power but at various scan speeds. The parallel scan lines making up each exposure were drawn approximately 50 μm apart. Based upon knowledge of the diameter of the focused beam at the liquid surface, the scan speed, the laser power, and the scan spacing, the summation of exposure mJ/cm² was calculated. Each square was allowed to float on the surface of the petri-dish for approximately 15 minutes. Then the squares were blotted and a thickness measurement was taken using Mitutoyo NTO25-8°C spring loaded Absolute Digimatic calipers. When the natural log of the exposures is plotted against the measured thickness a least squares fit line can be drawn. The D_p (μm) is the slope of the least

squares fit line. The E_c (mJ/cm^2) is the X-axis crossing point ($Y=0$) of the line. And the E10 is the energy necessary to produce a layer approximately 10 mils ($254\ \mu\text{m}$) thick. In general, the lower the E10 number, the faster the photospeed of the composition.

Having described specific embodiments of the present invention, it
5 will be understood that many modifications thereof will readily be apparent to those skilled in the art, and it is intended therefore that this invention is limited only by the spirit and scope of the following claims.